

IceCube sensitivity for neutrino flux from Fermi blazars in quiescent statesA. Neronov^{1,2} and M. Ribordy³¹*ISDC Data Centre for Astrophysics, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland*²*Geneva Observatory, 51 ch. des Maillettes, CH-1290 Sauverny, Switzerland*³*High Energy Physics Laboratory, EPFL, CH-1015 Lausanne, Switzerland*

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We investigate the IceCube detection potential of very high energy neutrinos from blazars, for different classes of hadronic models, taking into account the limits imposed on the neutrino flux by the recent *Fermi* telescope observations. Assuming the observed γ -ray emission is produced by the decay of neutral pions from proton-proton interactions, the measurement of the time-averaged spectral characteristics of blazars in the GeV energy band imposes upper limits on the time-averaged neutrino flux. Comparing these upper limits to the 5σ discovery threshold of IceCube for different neutrino spectra and different source locations in the sky, we find that several BL Lacs with hard spectra in the GeV band are within the detection potential of IceCube. If the γ -ray emission is dominated by the neutral pion decay flux, none of the flat-spectrum radio quasars are detectable with IceCube. If the primary high energy proton spectrum is very hard and/or neutrinos are produced in proton photon, rather than proton-proton reactions, the upper limit on the neutrino flux imposed by the measured γ -ray spectra is relaxed and gamma-ray observations impose only lower bounds on the neutrino flux. We investigate whether these lower bounds guarantee the detection of blazars with very hard neutrino spectra (spectral index $\Gamma_\nu \sim 1$), expected in the latter type model. We show that all the hadronic models of activity of blazars are falsifiable with IceCube. Furthermore, we show that models with γ -ray emission produced by the decay of neutral pions from proton-proton interactions can be readily distinguished from the models based on proton-gamma interactions and/or models predicting very hard high energy proton spectra via a study of the distribution of spectral indices of γ -ray spectra of sources detected with IceCube.

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I. INTRODUCTION

The broadband, radio-to- γ -ray spectra of blazars are most commonly interpreted within the framework of synchrotron-self-Compton (SSC) or synchrotron-external-Compton (SEC) models [1–5]. Within this framework, the observed γ -ray emission is generated via inverse Compton (IC) scattering of low energy background photons. The background photons originate either from an external source (in synchrotron-external-Compton models) or are produced by the same high energy electrons via the synchrotron mechanism (synchrotron-self-Compton models).

An alternative interpretation of the γ -ray emission is considered in models involving interactions of high energy protons [6–8]. Several types of such hadronic interaction models are considered in the literature. Different models adopt different assumptions about the dominant interaction channel of high energy protons and about the high energy proton spectrum.

If high energy protons interacting with low energy protons is the dominant channel (e.g. from the accretion flow onto a supermassive black hole), a significant contribution to the observed γ -ray flux could be secondary emission from the decay of neutral pions $\pi^0 \rightarrow \gamma\gamma$. Indeed, if one assumes a “conventional” E^{-2} power-law-type spectrum of high energy protons (see e.g. [9]) generated, for instance, by proton shock acceleration in the blazar jet, one finds that the spectrum of γ ray produced by the π^0 decay

should be distributed over a broad range of energies, starting from a fraction of the pp reaction energy threshold $E_{pp,thr} = 2m_\pi(1 + m_\pi/m_p) \simeq 280$ MeV, where m_p , m_π are proton and pion masses, up to the high energy cutoff of the proton spectrum. In contrast, if the high energy protons interact mostly with the background photons, the reaction threshold is kept high $E_{p\gamma,thr} = (m_p m_\pi + m_\pi^2)/\epsilon \simeq 6.8 \times 10^{16} [\epsilon/1 \text{ eV}]^{-1}$ eV, where ϵ is the energy of the background photon. Consequently, the observed γ -ray emission from blazars, detected at energies $E_\gamma \ll E_{p,thr}$, cannot be produced by neutral pion decay. Instead, the observed γ -ray emission in this type of models is usually supposed to be produced by secondary electron-positron pairs generated in proton interactions and/or in electromagnetic cascade initiated by the proton interaction.

A similar “proton-initiated cascade” origin of the observed γ -ray emission is assumed in models which consider the possibility of very hard spectra of high energy protons or proton spectra with low energy cutoffs (see e.g. [10–16]). Such hard proton spectra can be produced if protons are accelerated by large-scale electric fields induced close to the black hole horizon, rather than at shocks in the blazar jets. Arguments in favor of particle acceleration directly in the central engine of active galactic nuclei (AGN) are given by the recent observations of very fast variability of high energy γ -ray emission from blazars and radio galaxies (see e.g. [14,15,17]).

A straightforward distinction between hadronic and leptonic models and between different types of hadronic models of emission from blazars would follow from the detection of high energy neutrinos expected to accompany γ -ray emission in hadronic models only. However, experimental limitations have prevented positive outcomes until recently. First, the sensitivity of existing high energy neutrino detectors was not sufficient to detect neutrino flux even from the brightest blazars. Search results for neutrino signal from astronomical point sources have, until now, only provided upper limits [18–22] usually above model predictions. Next, the quality of the available γ -ray data was not sufficient to make firm predictions of the time-averaged (over flaring and quiescent states, taking into account flaring “duty cycles”) neutrino fluxes from blazars expected in different hadronic emission models.

With the newly operating IceCube [23] and Fermi [24] telescopes, a new sensitivity window on high energy neutrinos is currently opening (see e.g. [25], where the IceCube science potential has been generically described or [26,27], regarding galactic sources) and the detection of quiescent (time-averaged) levels of γ -ray emission from a large number of blazars has become possible. In this paper, we discuss the implications of the time-averaged γ -ray spectral measurements of a large number of blazars for the detection of neutrinos from this class of sources by IceCube.

Under the assumption of an observed γ -ray emission in the GeV energy band dominated by neutral pion decay, the time-averaged neutrino flux from blazars can be predicted. Assuming a simple power-law-type spectrum of the primary high energy protons, the measurement of the π^0 decay flux and spectral index in the GeV band fully constrains the expected neutrino flux at higher energies. Using the first published Fermi catalogue of blazars and AGN (normalization and spectral characteristics) [28], the corresponding neutrino fluxes for each blazar are calculated. Once these neutrino fluxes convolved to the instrumental response of IceCube for sources at different declinations, the expected number of neutrinos for each blazar is derived. This analysis leads us to conclude a detectable steady-state neutrino emission from a few (out of $\sim 10^2$) Fermi blazars with the hardest spectra in the GeV band.

If the observed γ -ray emission is dominated by the synchrotron and/or inverse Compton and/or bremsstrahlung emission from the secondary e^+e^- pairs produced in proton-initiated particle cascades, the constraints on the neutrino flux from the source are significantly weaker, since the measurement of the GeV-band γ -ray spectrum does not provide a direct constraint on the neutrino spectrum. We demonstrate this possibility by considering a model in which a nearly monoenergetic proton beam (composed of e.g. protons accelerated in a vacuum gap in a black hole magnetosphere) produces γ rays and neutrinos in proton-proton interactions (e.g. during the propagation through the accretion flow).

By combining IceCube and Fermi data, we show that it should be possible to (a) confirm or disprove the hadronic models of activity of blazars and (b) firmly distinguish between models which predict very hard neutrino spectra (which could be either due to the low energy cutoffs in the proton spectra or due to the threshold effects of the proton-photon interactions) and models which assume relatively soft (E^{-2} -like) neutrino spectra). This would proceed via a study of the distribution of neutrino-detected blazars in a γ -ray “flux vs photon index” diagram in the GeV band: In the scenario with neutral pion decay γ -ray emission from proton-proton interactions, all the blazars detected with IceCube should occupy the “high flux—hard spectrum” corner of the diagram, while they should be randomly distributed in the models based on $p\gamma$ interactions and/or proton spectra with low energy cutoffs.

The plan of the paper is as follows: In Sec. II, we consider a specific hadronic model of blazar activity which assumes γ -ray emission produced a power-law distribution of high energy protons (with a relatively soft spectra) in interaction with low energy protons from the accretion flow. We show that in this class of models, the spectral characteristics of the GeV-band γ -ray emission are directly related to the spectral characteristics of neutrino emission. In Sec. III, we derive the time-averaged neutrino flux from blazars detected in the GeV energy band by the Fermi telescope and demonstrate that only blazars with the hardest GeV-band spectra can be expected to be detectable as neutrino sources.

Next, in Section IV we present a specific hadronic model which predicts a very hard neutrino spectrum. We demonstrate that in this class of models, measurements of the GeV-band γ -ray spectra by *Fermi* impose only lower bounds on the neutrino flux, but do not constrain the spectral characteristics of the neutrino signal. We discuss the numerous uncertainties affecting the neutrino flux estimates. In Sec. V, we investigate whether blazars with very hard neutrino spectra can be detected with IceCube. One immediate problem for the detection of sources with very hard spectra is related to the Earth opacity to neutrinos with energies above \sim PeV, which dominate the source flux. The statistics of the neutrino signal at increasing source declinations is therefore reduced. We then derive the IceCube spectral discovery curves for arbitrary source declinations. Finally, in Sec. VI, we investigate whether the hadronic model(s) of blazar activity are falsifiable with IceCube and whether different types of hadronic models can be distinguished using a combination of IceCube and Fermi data.

II. GEV γ -RAY EMISSION FROM NEUTRAL PION DECAY

If the high energy protons are produced via shock acceleration, their spectrum is expected to be roughly a cutoff powerlaw with a spectral index $\Gamma_p \sim 2$, $dN_p/dE \sim E^{-\Gamma_p} \exp(-E/E_{p,\text{cut}})$. If collision of high energy protons

with low energy protons is the main interaction channel (e.g. from the accretion flow onto supermassive black hole, or with protons populating the blazar jet), both the π^0 decay γ ray and the neutrino spectra are cutoff power laws with approximately the same indices $\Gamma_\nu \simeq \Gamma_\gamma \simeq \Gamma_p$, in a wide energy interval from ~ 0.1 GeV up to a cutoff at energies somewhat smaller than that of the primary proton spectrum $E_{\gamma,\nu,\text{cut}} \simeq KE_{p,\text{cut}}$ with $K \sim 0.1$ [29].

Naively, the similarity between the γ -ray and neutrino spectra should enable to predict the blazar neutrino emission characteristics if the γ -ray emission spectrum is known. The IceCube telescope being most sensitive to neutrinos with energies above ~ 1 TeV, the knowledge of the γ -ray source spectrum in this energy band is most important to estimate the detectability of the neutrino signal. However, in the case of extragalactic sources, the γ -ray flux at energies above ~ 10 GeV–1 TeV is attenuated by pair production on the background radiation fields (collectively known as extragalactic background light, EBL). This degrades the information carried by the shape and overall flux of the π^0 decay spectrum of the source. This, in turn, prevents a direct assessment of source detectability with a neutrino telescope. Even for relatively low redshift sources, such as TeV γ -ray loud blazars, measurements of source spectra above 100 GeV do not provide information about the source neutrino spectra. This is illustrated in Fig. 1, in which we show a model fit for the GeV–TeV band emission spectrum of the blazar PG 1553 + 11, recently measured by the Fermi, HESS, and MAGIC

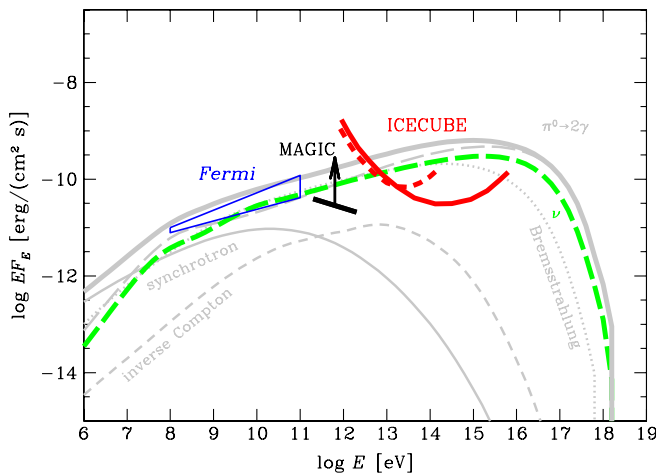


FIG. 1 (color online). Spectra of γ -ray and neutrino emission of blazar PG 1553 + 11 expected in a model in which the GeV emission is dominated by the γ rays from neutral pion decay. The thin solid, short dashed and dotted lines show the contributions from synchrotron, inverse Compton and bremsstrahlung emission from the secondary e^+e^- pairs. The two curves marked IceCube show the discovery potential of IceCube to the power-lawlike neutrino spectra with different spectral indices, for different source declinations: 15° (thick solid red curve) and 75° (thick dashed red curve), derived in Sec. V.

telescopes. The TeV band observations result only in a lower bound on (rather than measurement of) the source γ -ray flux (see e.g. [30]).

Contrary to TeV γ rays, γ rays in the GeV energy band do not suffer from the absorption on the EBL. Measurements of the spectral characteristics in this energy band provide therefore information about the intrinsic spectrum of the blazar. Since the π^0 decay spectrum is expected to extend down to sub-GeV energies in models based on proton-proton interaction, a measurement of the spectral characteristics in the GeV energy band could be used to constrain the π^0 decay spectrum. Assuming a power-law primary proton spectrum, the intrinsic γ -ray spectrum of the source in the TeV energy range can be reconstructed and the neutrino flux from the measurements of the flux and spectral index of the γ -ray emission in the GeV band can be estimated.

This possibility is illustrated in Fig. 1, in which we show the results of a numerical calculation of the γ -ray and neutrino spectra produced in proton-proton interaction of high energy protons with a power-law spectrum with an index of $\Gamma_p = 1.8$ and a high energy cutoff at $E_{p,\text{cut}} = 10^{18}$ eV, with low energy protons from the (radiatively inefficient) accretion flow onto a $10^7 M_\odot$ black hole. Our model is identical to the model of high energy emission from the cascade developing at the base of the jet of a TeV blazar, PKS 2155 – 304, developed in the Ref. [15]. Protons are initially accelerated close to the black hole horizon (at the distance $D \sim 10^{12}$ cm) and escape to large distances (our calculation stops at $D = 10^{16}$ cm). Interaction with protons of the accretion flow (see [15] for the detailed description of the geometry of the radiatively inefficient accretion flow) initiate a particle cascade which accompanies the escape of the high energy protons. The cascade leads to the generation of neutrino and γ -ray emissions, calculated using the analytical approximations for the production spectra of secondary particles in pp interaction derived by Kelner et al. [31].

From Fig. 1, one can see that the GeV-band emission is dominated by (or, at least, has a significant contribution from) the π^0 decay emission component, which has a spectral energy distribution very similar to the one from neutrinos. This enables an estimate of the characteristics of neutrino spectrum from the GeV-band γ -ray spectrum.

One should note that, apart from the π^0 decay emission, the γ -ray spectrum in the GeV band could have contributions from synchrotron, inverse Compton and bremsstrahlung emission produced by the secondary e^+e^- pairs. Such e^+e^- pairs are produced by charged pion decay and/or in result of the development of electromagnetic cascade inside the blazar jet. In the pure hadronic model of blazar activity, where all the high energy electrons and positrons are supposed to be produced in this way, the power injected in electrons/positrons from the π^\pm decay is at most comparable to the power injected into π^0 decay γ rays. If the

primary proton spectrum is relatively soft $\Gamma_p \sim 2$, the power transferred to the e^+e^- pairs by the electromagnetic cascade is also at most comparable to the initial π^0 decay γ -ray power. This means that in models based on proton-proton interaction with soft high energy proton spectra, a significant contribution in the GeV-band γ -ray emission is given by the π^0 decay component, in spite of the possible presence of synchrotron, inverse Compton and/or bremsstrahlung emission components. This ensures the possibility to estimate the neutrino signal from the detected GeV γ -ray signal.

III. DETECTABILITY OF QUIESCENT NEUTRINO EMISSION FROM BLAZARS IN THE LIGHT OF FERMI

Measurements of the spectra of quiescent emission from blazars at energies below 10 GeV became possible recently with the start of operation of the Fermi telescope. Measurements of the spectral parameters of the γ -ray emission from blazar, reported in [28], enables one, for the first time, to make predictions of the time-averaged neutrino flux within the hadronic model of activity, under the assumption that the GeV-band flux is dominated by the π^0 decay contribution.

The resulting estimates of the number of neutrinos from different blazars, given one year of IceCube exposure (in the 80 string baseline configuration) [23] are shown in

Table I (only blazars with an expected number of neutrinos close or above the 5σ "discovery" threshold are listed).

The 5σ discovery threshold is calculated using the declination-dependent atmospheric neutrino background parametrization from [32] (which includes the "prompt" ν_μ flux). The prompt component is as yet uncertain and may significantly contribute to the overall atmospheric neutrino spectrum at energies above $E \sim 10^{5-6}$ GeV.

The diffuse neutrino emission from the interaction of galactic cosmic rays with the interstellar medium estimated, for instance in Ref. [33], has been neglected: While expected to be relatively important for sources at low galactic latitudes $b \sim 0^\circ$, but not exceeding the prompt atmospheric neutrino component, it is largely subdominant at large galactic latitudes.

The diffuse neutrino emission from unresolved blazars was neglected as well. Within the proton-proton interaction models considered above and based on early measurements of the EGRET extragalactic diffuse γ -ray background by [34], the diffuse extragalactic neutrino flux was estimated to eventually dominate the atmospheric neutrino flux above $E \sim 10^5$ GeV [35]. However, revised measurements of the extragalactic diffuse γ -ray background with EGRET indicate a lower normalization and a softer background spectrum [36] thus accordingly reducing this neutrino background component from a rescaling of the estimates in Ref. [35] to a level well below the atmospheric neutrino flux at $\sim 10^5$ GeV.

TABLE I. List of blazars with potentially detectable quiescent neutrino emission, in the model with γ -ray flux in the Fermi band dominated by neutral pion decay. Bold names: blazars detected in the TeV energy band. The blazars in the Southern hemisphere are not accessible to IceCube. The two last columns list the expected number of detected signal and atmospheric neutrinos, n_s and n_b , together with the estimated 5σ discovery threshold, $n_{5\sigma}$ for two choices of the reconstructed low muon energy threshold. $E_\mu^{\min,1}$ and $E_\mu^{\min,2}$ (see text).

Name	Fermi Name	z	Γ_γ	F	$(n_s, n_b, n_{5\sigma})_{E_\mu^{\min,1}}$	$(n_s, n_b, n_{5\sigma})_{E_\mu^{\min,2}}$
Blazars above 5σ detection threshold						
B3 0133 + 388	0FGL J0136.6 + 3903	(?)	1.65	1.8	(14, 0.36, 7)	(4.6, 0.0079, 3)
1ES 1011 + 496	0FGL J1015.2 + 4927	0.212	1.73	4.9	(12, 0.31, 7)	(3.1, 0.0067, 3)
Mrk 421	0FGL J1104.5 + 3811	0.0300	1.77	15.3	(27, 0.36, 7)	(7.7, 0.0080, 3)
PKS 1424 + 240	0FGL J1427.1 + 2347	(?)	1.80	6.2	(11, 0.53, 8)	(3.6, 0.013, 3)
PG 1553 + 11	0FGL J1555.8 + 1110	0.36(?)	1.70	8.0	(71, 0.95, 10)	(31, 0.024, 4)
Mrk 501	0FGL J1653.9 + 3946	0.0337	1.70	3.1	(13, 0.35, 7)	(3.9, 0.0077, 3)
PKS 1717 + 177	0FGL J1719.3 + 1746	(?)	1.84	6.9	(7.9, 0.67, 8)	(2.8, 0.017, 4)
Blazars close to 5σ detection threshold						
3C 66A	0FGL J0222.6 + 4302	0.444	1.97	25.9	(3.3, 0.34, 7)	(0.74, 0.0076, 3)
AO 235 + 164	0FGL J0238.6 + 1636	0.94	2.05	72.6	(5.2, 0.70, 9)	(1.5, 0.018, 4)
1ES 0502 + 675	0FGL J0507.9 + 6739	0.416	1.67	1.7	(4.8, 0.24, 6)	(0.91, 0.0038, 3)
B 1218 + 30	0FGL J1218.0 + 3006	0.182	1.89	9.7	(4.3, 0.43, 7)	(1.2, 0.010, 3)
W Com	0FGL J1221.7 + 2814	0.102	1.93	8.3	(2.3, 0.46, 7)	(0.63, 0.011, 3)
1ES 1959 + 650	0FGL J2000.2 + 6505	0.047	1.86	4.2	(1.3, 0.24, 6)	(0.20, 0.0041, 3)
Neutrino candidate blazars in Southern hemisphere						
KUV 0311 – 1938	0FGL J0033.6 – 1921	0.610	1.70	1.6		
PKS 2005 – 489	0FGL J2009.4 – 4850	0.071	1.85	2.9		
PKS 2155 – 304	0FGL J2158.8 – 3014	0.116	1.85	18.1		

The uncertainty of the diffuse neutrino background level at energies above $E \sim 10^5$ GeV may slightly modify the results of Table I, especially the numbers of neutrino-induced muon events with detector threshold energy $E_{\mu}^{\text{min},2} = 10^{4.5}$ GeV. On the other hand, the numbers of neutrino-induced muon events with detector threshold energy $E_{\mu}^{\text{min},1} = 10^{3.5}$ GeV remain almost unaffected, the dominant diffuse background source being the conventional atmospheric neutrino component.

To estimate the parameters of the neutrino spectrum (normalization Φ_{ν} and spectral index Γ_{ν}) from the observed parameters of the γ -ray spectrum (Φ_{γ} , Γ_{γ}), we produce a “lookup table” (Γ_{ν} , Φ_{ν}) vs (Γ_{γ} , Φ_{γ}) using the neutrino and γ -ray production spectra for different power-law distributions of the primary protons. We use the approximations of Kelner et al. [31] for the calculation of the production spectra and assume a fully oscillated neutrino flux (i.e. the normalization of the muon neutrino spectrum is 1/3 of the normalization of the primary total neutrino spectrum). The number of detected neutrinos from the source (and the contamination by the atmospheric neutrino background) depends on the low muon energy threshold chosen for the analysis. In Table I, we show the number of neutrinos from the source for two different choices of the reconstructed muon energy thresholds, $E_{\mu}^{\text{min},1} = 10^{3.5}$ GeV ≈ 3 TeV and $E_{\mu}^{\text{min},2} = 10^{4.5}$ GeV ≈ 30 TeV. In analyzing the data, the best choice for the reconstructed muon energy threshold depends on the neutrino spectral index Γ_{ν} . This issue is discussed in greater detail in Sec. V.

Out of 104 bright blazars detected by Fermi during the first three months of operation [28], only a few are expected to produce sufficiently high neutrino flux for a detection within 1 yr of IceCube operation. All the neutrino candidate blazars are BL Lac-type objects. None of the bright and powerful flat-spectrum radio quasars (FSRQ), such as 3C 279, 3C 273, or 3C 454.3, are expected to produce a neutrino flux above the IceCube detection threshold.

This is also clear from Fig. 2, where we show the thresholds of detectability of neutrino emission from Fermi blazars, calculated by normalizing the neutrino flux from the Fermi γ -ray spectra. In principle, the expected number of high energy neutrinos from the source depends not only on the intrinsic source spectrum, but also on the position of the source in the sky (given the specific location of IceCube at the South Pole on the source declination). Not only the number of source neutrinos, but also the atmospheric neutrino flux, which constitutes the background for the source signal, depend on the declination. Thus it follows a dependence of the 5σ source detection threshold on the declination. Figure 2 shows that the best candidates for a detection with IceCube (within proton-proton models with soft high energy proton spectra) are the low declination BL Lacs with hard GeV-band γ -ray spectra. All the bright FSRQ detected by Fermi are expected to produce neutrino counts

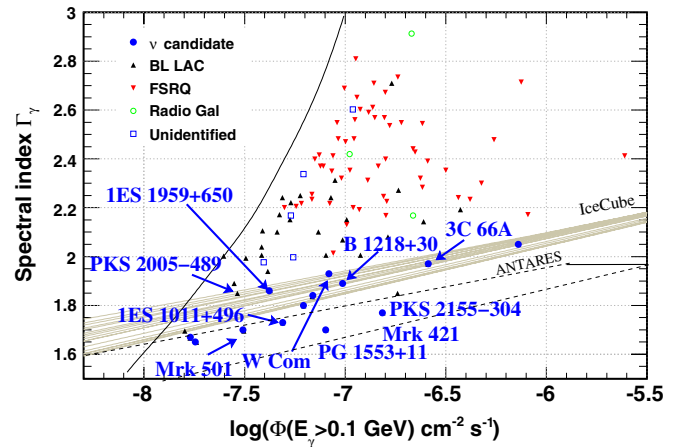


FIG. 2 (color online). Distribution of Fermi AGN in “flux vs spectral index” parameter space (from Abdo *et al.* [28]). Grey curves labelled IceCube show the 5σ discovery threshold for detection of neutrino signal from Fermi blazars by IceCube in the model in which γ -ray emission is dominated by the signal from neutral pion decay. Different curves correspond to different assumed source declinations, from $\delta = 5^\circ$ (upper curve) to $\delta = 85^\circ$ (lower curve) with a $\Delta\delta = 5^\circ$ step. Below the 3 yr IceCube discovery curves are indicated the 1 yr ANTARES 90% C.L. upper limit curves, extracted and extrapolated from [39] (see text). Blue or filled circles correspond to Fermi blazars considered as “neutrino source candidates” in the model with neutral pion decay γ -ray emission.

below the detection threshold of IceCube, independent of their declination.

To understand why the bright FSRQ are not detectable by IceCube, one has to take into account that the predictions for the neutrino flux depend not only on the normalization of the γ -ray spectrum at GeV energies, but also on its hardness. IceCube is most sensitive to neutrinos with energies above ~ 1 TeV. The harder the spectrum of the source in the GeV energy band, the higher the expected flux in the TeV-PeV band. It turns out that in the GeV band, FSRQ have spectra on average softer than BL Lacs and thus explains why the less luminous (in the GeV band) BL Lacs are expected to produce higher neutrino fluxes in the TeV-PeV band than FSRQs. These estimates rely, however, on an initially foreseen 80 string IceCube configuration and enhanced sensitivity to lower energy in the new 86 string baseline configuration has not been considered, yet [37].

It is worth mentioning that most of the best candidate sources listed in Table I are TeV γ -ray loud BL Lacs. Ten out of 16 sources have already been reported to be TeV emitters. The remaining 6 have either large or unknown redshift which explains the difficulty of their detection above 100 GeV. It is unlikely that the TeV blazar neutrino emission be produced in $p\gamma$ interaction, because a high efficiency of the $p\gamma$ interaction (which has a cross section $\sigma_{p\gamma} \sim 10^{-28}$ cm 2), would automatically imply a strong absorption of the TeV γ -rays via pair production on the

soft photon background in the source (the cross section for this process is $\sigma_{\gamma\gamma} \approx 10^{-25} \text{ cm}^2$, i.e. 3 orders of magnitude larger than the $p\gamma$ cross section) [13,38]. The only possibility for neutrino production in TeV blazars is via proton-proton interactions.

The detection potential of ANTARES for the strongest neutrino emitters can also be roughly estimated using the 1 yr E^{-2} 90% C.L. upper limit curves found in Ref. [39] ($E^2 d\Phi_{\nu_\mu}/dE_\nu \approx 4\text{--}10 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}$ over the declination range $-90^\circ < \delta < 30^\circ$), assuming a behavior similar to IceCube for hardening spectra (i.e. by extrapolating parallel to IceCube 5σ discovery curves). The expected signal escapes ANTARES discovery potential for all sources but for PG 1553 + 11, which could be in the reach of ANTARES after 1 yr. Note, however, that this assumption may not hold, see Appendix A, given the distinct detector response of ANTARES and IceCube.

IV. HADRONIC MODELS WITH VERY HARD NEUTRINO SPECTRA

The above IceCube neutrino count estimates from blazars show that within the hadronic models predicting relatively soft neutrino spectra (E^{-2} like), ≤ 10 γ -ray loud blazars with hardest GeV-band γ -ray spectra can be detected within a several yearlong neutrino data set.

Although experimental results in the literature usually consider benchmark power-law-type neutrino spectra $dN_\nu/dE \propto E^{-\Gamma_\nu}$ with $\Gamma_\nu \sim 2$, most existing hadronic models of blazar activity predict neutrino spectra which significantly differ from a E^{-2} powerlaw. This is often related to the existence of a low energy cutoff in the proton spectra. As it is mentioned in the Introduction, these low energy cutoffs can be either intrinsic cutoffs in the proton spectra (e.g. in the models with proton acceleration in the blazar central engine) or can arise due to the existence of a threshold energy of proton-photon interactions.

Since the low energy cutoff or the photo-pion threshold energy, considered in most of the hadronic models, is much higher than ~ 1 PeV, the contribution of the π^0 decay component to the γ -ray emission spectrum in the GeV-TeV energy band is small, compared to the synchrotron and/or inverse Compton and/or bremsstrahlung emission from the secondary e^+e^- pairs produced in the decay of the charged pions and/or in electromagnetic cascade. Therefore the estimates of the expected spectral characteristics of neutrino emission based on the spectral characteristics of the GeV-band γ -ray emission, presented above, do not work.

To demonstrate this, we show in Fig. 3 the result of calculation of the γ -ray and neutrino spectra in the same model as in Fig. 1, but assuming a very hard high energy proton injection spectrum, with $\Gamma_p \approx 0$ (i.e. most of the power of the primary proton beam is carried by protons with energies close to the assumed cutoff energy $E_{p,\text{cut}} = 10^{18} \text{ eV}$). One can clearly see that a satisfactory fit of the

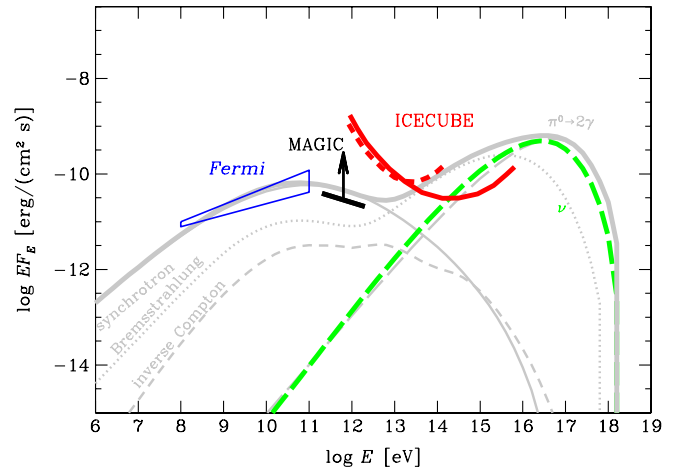


FIG. 3 (color online). Spectra of γ -ray and neutrino emission of blazar PG 1553 + 11 expected in a model with GeV emission dominated by γ rays from secondary e^+e^- pairs. The notations are the same as in Fig. 1.

GeV-TeV γ -ray spectrum is achieved with the dominant contribution from synchrotron emission from the secondary electrons. No information on the π^0 decay spectrum and hence no information about the neutrino spectrum can be extracted from the available γ -ray data.

The hypothesis of hard neutrino spectra opens a possibility of strong neutrino emission, even in the quiescent state, from a large number of blazars, including both BL Lacs and FSRQs.

It was argued in Ref. [40] that even if the GeV-TeV band γ -ray emission is dominated by the flux from electron-positron pairs from π^\pm decay, constraints on the neutrino luminosity of the source can still be derived from the spectra of the broad band γ -ray emission. Namely, a measurement of the overall bolometric luminosity of a galactic γ -ray source imposes a restriction on its neutrino luminosity (but not on the spectral index or cutoff energy of the neutrino spectrum).

In the case of extragalactic sources, measurements of the electromagnetic luminosity of the source also imposes a restriction on its neutrino luminosity. However, the relation between the observed γ -ray power and morphology of an extragalactic source and its neutrino luminosity is more complicated than in the case of a galactic source.

The problem being that it is possible that even for sources at small redshifts, most of the γ -ray power initially emitted in the energy band above 0.1–1 TeV is absorbed during propagation through the intergalactic medium due to pair production on the EBL. This means that the primary source power produced in result of proton interaction is not known. At the same time, to obtain a correct estimate of the neutrino luminosity, one has to be able to estimate the primary source power at energies above 0.1–1 TeV. This could, in principle, be done because the absorbed power is initially converted into e^+e^- pairs and then back to the

γ -rays, because the e^+e^- pairs lose energy via inverse Compton scattering on the cosmic microwave background (CMB) photons. Measuring the flux of the inverse Compton emission from the γ -ray-induced cascade e^+e^- pairs, one would be able to measure the flux of the initial γ -rays and in this way to measure the γ -ray luminosity of the primary source.

The method of measurement of the flux from the γ -ray-induced cascade e^+e^- pairs heavily depends on the strength of the extragalactic magnetic fields. If the extragalactic magnetic fields are strong $B \gg 10^{-12}$ G, the trajectories of the e^+e^- pairs produced in the process of absorption of the γ -rays on the EBL would strongly deviate before they transfer energy through inverse Compton scattering to the CMB photons [41]. The emission from the γ -ray-induced cascade should therefore be detectable as an extended γ -ray halo around the primary point source. The size of the halo is determined by the mean free path of the γ -rays through the EBL and thus depends on the primary γ -ray energies. The luminosity of the halo is equal to the γ -ray luminosity of the primary source in the TeV-EeV energy band, averaged over 10^3 – 10^6 yr time scale.

If the extragalactic magnetic fields are somewhat weaker $10^{-16} \ll B \ll 10^{-12}$ G, the deflection of e^+e^- pairs over the radiative cooling time would be moderate, but still the signal from the γ -ray induced cascade in the intergalactic medium could also be detected as an extended emission region around an extragalactic point source [42,43], with the source size having a somewhat different dependence on the energy than for halos discussed by Aharonian et al. [41].

Finally, if the magnetic fields in the intergalactic medium are $B \ll 10^{-16}$ G, the extended emission from the γ -ray-induced cascade in the intergalactic space is indistinguishable from the point source emission because the size of the extended source becomes smaller than the point spread function of the current generation γ -ray telescopes [44]. In this case, a measurement of the point source flux provides a good estimate of the total electromagnetic and neutrino power of the source.

One should note, however, that at present, the strength of the extragalactic magnetic fields is largely unknown and the expected extended γ -ray emission from the extragalactic sources is not detected. This means that the luminosity of the GeV-TeV γ -ray loud blazars at energies above several TeV is largely unconstrained and, as a consequence, the neutrino luminosity of the blazars is not constrained by the γ -ray data.

The overall luminosity of the source, generated by the interaction of high energy protons, is larger or equal to the power contained in electromagnetic cascades, which transfer the initial source power to the sub-TeV energy band. Since the total electromagnetic luminosity of the source is comparable to its neutrino luminosity, measurement of the source flux in the sub-TeV energy band provides a lower

bound on the neutrino luminosity of the source. Taking this fact into account, we show the calculated neutrino flux in Fig. 3 as a lower limit on the expected neutrino flux, obtained under the assumption of an observed γ -ray luminosity of the source comparable to its intrinsic γ -ray luminosity.

From the discussion of this section, it is clear that the search for very hard neutrino sources is extremely important in the context of the study of blazar activity mechanisms. It is not clear a priori, if neutrino sources with very hard spectra, with most of the energy output in the >10 PeV energy band, are accessible for study with IceCube. The problem being that at energies >10 PeV, Earth is not transparent to neutrinos. Thus most of the signal from the source is absorbed in Earth and does not reach the detector. To the best of our knowledge, no comprehensive study of sensitivity of IceCube to sources with very hard neutrino spectra was published up to now. Taking this into account, we investigate, in the following section, the potential of IceCube for the detection of neutrino sources with very hard spectra extending to the multi-PeV-EeV energies.

V. ICECUBE SENSITIVITY FOR ASTRONOMICAL SOURCES WITH HARD NEUTRINO SPECTRA

The sensitivity of a neutrino telescope to a flux model can be derived from the knowledge of the neutrino effective area of the telescope at the source declination (from the available information in publications, usually a declination-averaged effective area) and the angular and energy resolution of the instrument together with the assumption of an atmospheric neutrino flux. Nevertheless, this compact approach suffers limitations owing to the fact that the knowledge of the neutrino effective area alone does not permit the derivation of the optimal sensitivity to an arbitrary neutrino flux shape, as detailed information on the detector response is hidden behind the neutrino effective area concept.

A refined method to assess the potential of a neutrino telescope to an arbitrary flux and arbitrary declination is based on the detector muon effective area and differential muon flux at the detector, which can both be, respectively, extracted from the averaged neutrino effective area and from the neutrino flux spectrum propagated through Earth following the methodology introduced by Neronov and Ribordy [40]. From the interplay of neutrino signal contamination by atmospheric neutrinos and neutrino absorption, the optimal reconstructed muon energy threshold for highest sensitivity for arbitrary spectral index and declination can be calculated: While for hard spectra, it is advantageous to suppress low energy events dominated by atmospheric neutrinos in order to increase the discovery potential, with larger declinations the increasing neutrino absorption may play an important role above 10–100 TeV

on defining the optimal reconstructed muon energy threshold.

Based on this method, not only the best sensitivity can be derived but also the possibility of detailed study of the source spectrum is opened, provided sufficient statistics avoiding the unfolding of the measured muon spectrum. We apply the recipe from Neronov and Ribordy [40] for the calculation of the event rate in terms of reconstructed muon instead of neutrino energies. This approach presents several advantages including the possibility of exploiting some of the physical observables (such as reconstructed energy) for the optimization of IceCube performance for the detection of sources with different spectral characteristics.

IceCube ‘‘Spectral discovery curves’’

A major challenge for the detection of astronomical neutrino sources with IceCube is the separation of the source signal from the atmospheric neutrino background. If the spectrum of the source is harder than that of the atmospheric neutrino background, much of this background could be suppressed by selecting only higher-energy events, i.e. adjusting the reconstructed low muon energy threshold in the data analysis event selection. The optimal reconstructed low muon energy threshold, which maximizes the signal-to-noise ratio, depends, in general, on the shape (e.g. on the spectral index, for a power-law neutrino energy distribution) of the spectrum of the source neutrinos. The dependence of the optimal analysis parameters on the spectral properties of the source leads to a dependence of the detector sensitivity on the assumptions about the spectral properties of the source. As a result, the knowledge of the IceCube discovery limit (= normalization of the neutrino spectrum at a given reference energy) for a ‘‘reference’’ source spectral index does not allow to estimate the sensitivity limit for a different source spectrum.

In Appendix A, we demonstrate a convenient way of presenting the IceCube discovery limits for arbitrary assumptions about the neutrino spectrum slope of the source. The spectral discovery curves, shown Fig. 4 for various source declination, bear the following meaning: A neutrino flux with spectral index Γ_ν (corresponding to a straight line in the $\log(E)$ vs $E^2 \log(\text{Flux})$ representation) tangent to one of the spectral discovery curve is at the limit of discovery. This representation of the IceCube discovery limit(s) is useful because it enables

- (i) The estimate of the IceCube sensitivity for arbitrary assumptions about the slope of the neutrino spectrum (i.e. the normalization of the minimal detectable spectrum at a given reference energy);
- (ii) The estimate of the neutrino energy range contributing most significantly to the source signal (the energy at which the minimal detectable source spectrum touches the discovery curve).

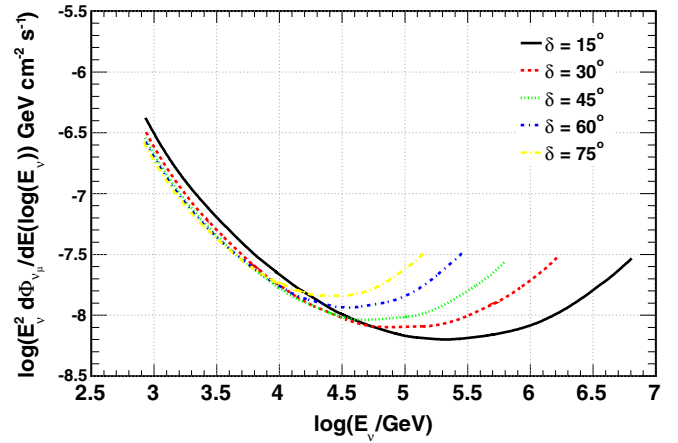


FIG. 4 (color online). IceCube point source reach after three years of exposure. The tangent to one of these curves intersecting the y-axis at 1 GeV defines the muon neutrino flux normalization for the corresponding declination.

The dependence of the discovery curves, Fig. 4, on the source location in the sky is reduced to the source declination δ , given the privileged location of IceCube at the South Pole. We notice a weak dependence of the discovery limit on the source declination in the case of soft neutrino sources ($\Gamma_\nu \gg 2$): Most events contributing to the source signal have relatively low energies, at which Earth is transparent for neutrinos. For sources with hard spectra $\Gamma_\nu \ll 2$, the IceCube discovery potential is strongly affected by the increase of the source declination. The rise of Earth absorption probability with energy obscures the source signal, contributed mostly by high energy neutrinos. The effect is most dramatic for the hardest neutrino spectra $\Gamma_\nu \simeq 1$. In this case, the minimal detectable flux for the sources at the declination $\delta = 75^\circ$ is about 1.5 orders of magnitude higher than from sources at $\delta = 15^\circ$.

VI. DISCUSSION: ICECUBE POTENTIAL FOR THE STUDY OF THE ORIGIN OF HIGH ENERGY BLAZAR ACTIVITY

The IceCube sensitivity curves, shown in Fig. 4, can be directly applied to estimate the detectability of neutrino emission from Fermi blazars both in the model with π^0 decay origin of the γ -ray spectrum and with the γ -ray emission from the secondary e^+e^- pairs. We demonstrate this on the example of the model calculations for the TeV γ -ray loud blazar PG 1553 + 11. The red or thick curves in Figs. 1 and 3, marked ‘‘IceCube,’’ show the IceCube discovery curves for the source declinations $\delta = 15^\circ$ (close to the actual declination of PG 1553 + 11) and $\delta = 75^\circ$. The expected neutrino spectrum (thick green long-dashed line) clearly intersects the IceCube discovery curves in both figures. Therefore if the source activity is determined

solely by acceleration and subsequent interactions of protons, the source should be detectable independent of the assumptions made about the origin of the GeV-band γ -ray flux: The detection or nondetection of several blazars with IceCube will confirm or rule out the so-called hadronic models of blazar activity.

Note that, although the expected neutrino signal from PG 1553 + 11 in Figs. 1 and 3 were calculated within the framework of a particular model of high energy proton interaction in the source (interaction with low energy protons from a radiatively inefficient accretion flow) developed in Ref. [15], the numerical estimates of the overall flux and spectral characteristics of the neutrino signal from the sources are, in a sense, model independent.

Indeed, on the one hand, in all hadronic models of blazar activity, which assume the high energy γ -ray emission dominated by the emission from the neutral pion decay, the normalization and the spectral characteristics of the neutrino flux are constrained by the measurements of the γ -ray flux in the GeV band in a similar way.

On the other hand, in all hadronic models which assume that the GeV-band γ -ray emission is dominated by synchrotron and/or inverse Compton and/or bremsstrahlung emission from the e^+e^- pairs produced in the charged pion decay, the measurement of the GeV-band γ -ray flux imposes a lower bound on the neutrino luminosity of the source (the neutrino luminosity should be larger or equal to the measured γ -ray luminosity). The shape of the neutrino spectrum at energies much below the threshold or low energy proton spectrum cutoff does not depend on the details of the proton spectrum itself: It is determined by the energy dependence of the differential cross section of proton interaction and charged pion decay spectrum. This means that in any model with γ -ray emission from secondary e^+e^- pairs, the expected neutrino flux is at least as high as the one shown in Fig. 3 and therefore detectable with IceCube, provided a low energy cutoff of the proton spectrum or the threshold energy of proton-photon interaction not higher than $\sim 10^{18}$ eV (see Fig. 3).

To summarize, we have explored the IceCube potential introducing a generic method to derive power-law type spectra discovery thresholds for an arbitrary neutrino spectral index ($1 \leq \Gamma_\nu \leq 4$) and for an arbitrary declination. In light of Fermi, the IceCube potential in the search for blazar neutrino point sources is promising even for quite different types of hadronic models of activity: After three years of exposure, several sources should be revealed independently of the details of the hadronic models. Detection or nondetection of the TeV sources PG 1553 + 11 and Mrk421 with the data collected by the IceCube collaboration between 2007 and 2009 would already set strong constraints on the model with the soft spectrum of proton injection.

Moreover, we established that IceCube will provide a definite answer regarding the validity of the hadronic class

of models of activity, ruling them out in the case of no discovery.

In contrast, the first high energy neutrino source detections with IceCube would not only open a new observational window, IceCube would delineate the two classes of hadronic models of activity as well, from a concurrent study of the Fermi photon and IceCube neutrino indices: While detected blazars conforming to models predicting soft neutrino spectra will lie in the lower part of the diagram Fig. 2 (delimited by the IceCube curves), the ones conforming to models with hard neutrino spectra will be distributed over a large range of photon indices Γ_γ . The detection of blazars with IceCube would therefore truly mark the birth of multimessenger high energy neutrino astronomy.

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APPENDIX A: DERIVATION OF THE ICECUBE SPECTRAL DISCOVERY CURVES

The neutrino point source strength normalization for discovery as a function of the neutrino source spectral index can be derived from the calculations of the number of atmospheric and extraterrestrial neutrino-induced muon events. These limits turn out to critically depend on the angular and energy resolution functions of the apparatus due to the diffuse nature of the soft atmospheric neutrino background. The relative importance of the resolution functions depend strongly on the spectral shape of the point source neutrino flux. The sensitivity to hard spectra with cutoff energy above \sim PeV will predominantly depend on the energy resolution while soft spectra will be probed best with instruments showing improved angular resolutions (Existing instruments deployed either in ice or water do not combine optimal resolution functions, which largely depend on the medium properties. This holds to the Cherenkov photon “thermalization” power of the media, determined by the relationship between Cherenkov light absorption and scattering lengths: In ice, $\lambda_{\text{abs}} \gg \lambda_{\text{scat}}$, in water $\lambda_{\text{abs}} \approx \lambda_{\text{scat}}$. Therefore while instruments using ice as the Cherenkov photon transport medium show improved calorimetric properties, instruments deployed in water have better pointing capabilities for opposite reasons).

Our simplified calculation for the required number of observed events pointing back to a source for a 5σ C.L. discovery is based on Poisson probability, requiring $C_P(n_{\text{obs}} - 1, n_b) \geq \text{erf}(5/\sqrt{2})$, where n_s (n_b) is the number of signal (atmospheric) neutrino events, $n_{\text{obs}} = n_s + n_b$ and C_P is the Poisson cumulative distribution.

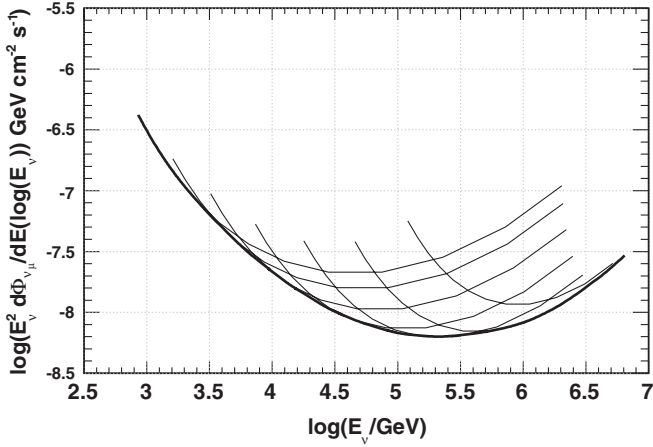


FIG. 5. Power-law limit representation of IceCube discovery potential. The thin curves (from left to right) corresponds to increasing reconstructed muon energy thresholds, from 100 GeV to 100 TeV, in step of 0.5 in $\log(E)$, for a declination $\delta = 15^\circ$. The thick curve is the envelope, representing the best possible reach following the selection method of reconstructed muon energy threshold.

For neutrino fluxes with spectral indices between $1 \leq \Gamma_\nu \leq 4$,

$$\frac{d\Phi_{\nu\mu}(E_\nu)}{dE_\nu} = \Phi_0 \times \left(\frac{E_\nu}{\text{GeV}}\right)^{-\Gamma_\nu}, \quad (\text{A1})$$

we calculate the “ 5σ discovery” flux normalization for a

series of reconstructed muon energy thresholds E_μ^{min} . Figure 5 illustrates the procedure leading to the derivation of the optimal potential by extraction of the envelope of curves from $\{\log(E_\nu^2 \frac{d\Phi_\nu}{dE_\nu}(E_\nu, \delta, E_\mu^{\text{min}}))\}_{E_\mu^{\text{min}}}$, calculated for the sources at different declinations δ . The meaning of each curve is the following: A power-law neutrino spectrum with normalization tangent to the thick curve is at the discovery limit.

Technically, the extraction of the envelope is performed in two steps instead of the single one as illustrated in Fig. 5: Once the best flux normalization $\Phi_0^{\text{min}}(\Gamma_\nu, \delta)$ is determined (the lower envelope of $\{\log\Phi_0(\Gamma_\nu, \delta, E_\mu^{\text{min}})\}_{E_\mu^{\text{min}}}$), the smooth thick curve from Fig. 5 is obtained from the envelope extraction from the series of curves $\{\log\Phi_0^{\text{min}}(\Gamma_\nu, \delta)\}_{\Gamma_\nu}$. The envelope condition reads

$$\log E_\nu = \frac{d \log \Phi_0^{\text{min}}}{d\Gamma_\nu}(\Gamma_\nu, \delta), \quad (\text{A2})$$

thus

$$\log\left(E_\nu^2 \frac{d\Phi_\nu}{dE_\nu}(E_\nu, \delta)\right) = \log\Phi_0^{\text{min}}(\Gamma_\nu, \delta) + (2 - \Gamma_\nu) \log E_\nu. \quad (\text{A3})$$

The results are shown Fig. 4 for various declinations and represent the IceCube discovery potential to power-law flux spectra.

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